

Conference Title

Indoor and Outdoor Characterizations of Photovoltaic Module Based on Multicrystalline Solar Cells

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Abstract

One of the main missions for the photovoltaic laboratory concerns the preparation and development of norms and standards for photovoltaic (PV) systems. To reach this objective, we have initiated a program research to identify the present of state of the art to develop specific measuring methods and test procedures for photovoltaic module and also, to develop laboratory test. Within this program we have executed since several years series of performance characterizations in indoor and outdoor testing on PV modules produced in industry and covering both series and prototype designs. This work describes the methodology, basic procedures and instrumental employed by our laboratory for the determination of photovoltaic module characteristics. According to this methodology, the main electrical and thermal parameters were determined for multicrystalline PV module under diverse conditions. The tests were based on IEC 61215 specification which had been prepared especially for this purpose and which are used as an international standard

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1. Introduction

The module is the most important component of the PV system due to two main reasons. The first reason is technologic concept because it is the component which converts the incident irradiance into electric power; and the second one is economic because the cost of modules is commonly upon 50% of the total cost of PV installations.

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These two reasons, among others, make necessary to conduct a suitable quality control of modules during the supply. Degradation is considered as the termination of the ability of a module to perform its primary function which is to provide safe, useful electric power. Usually, degradation of modules is not caused by one isolated factor, but it depends on multiple factors that interact causing degradation [1]. That interaction of factors is quite difficult to simulate in the laboratory.

According to manufacturers guarantee the module degradation average at Standard Test Conditions (STC) is below 1% per year in the first 10 years and below 0.8% per year in the module's complete life. The measurements procedures described in this paper are based on recommendations of IEC 61215. The function of qualification is to provide that assurance by subjecting representative samples to a series of test to identify environmental factors and design features, which could affect the attainment of a sufficiently long lifetime.

In addition to module design and performance requirements a series of characterizations and qualifications tests necessary to certify the module design and the necessary performance tests for acceptance of modules are already described in previous works [2,3,4]. The objective of this sequence is to determine the electrical and thermal characteristics of the module and to show as far as possible within reasonable constraints of cost and time that the module is capable of withstanding prolonged exposure in climates described in the scope. The actual lifetime expectancy of modules so qualified will depend on their design, their environment and the conditions under which they are operated.

The certification IEC 61215 of PV modules includes 17 tests which determine the thermal and electrical characteristics of the module. Also, the tests show that the modules are able to be exposed during large periods of time in outdoor conditions without failures. Regarding the quality control of a PV module supply, we must say that it is not possible to do all the tests in each module because of two reasons: several of them are destructive tests, and the realization of all non-destructive tests is too expensive. Also, it would be necessary a long time for the quality control. Actually the quality assurance program for PV installations which includes a PV module quality control with three tests of the IEC 61215 described as: Visual inspection (test 10.1); Maximum power measurement (test 10.2); Electrical isolation (test 10.3) and an additional nondestructive test as infrared thermographic and electroluminescence inspection PV Module quality control.

2. Experimental

In this study the tested PV module type, with the double glass encapsulation process, is the PWX500 module using Photowatt's multicrystalline solar cells technology. The solar cells are individually characterized and electronically matched prior to interconnection. The area of each solar cell is 100 cm^2 . Solar cells are arranged in 36 series connected cells configuration as 9x4 serial configuration strings and encapsulated in UV stabilized and weather-resistant polymers to form PV laminates. The PV module receives an electrical performance (I-V) test under standard controlled indoor conditions at STC condition (100 mW/cm^2 , AM1.5 global spectrum, 25°C) in accordance to IEC 904-4. We use a calibrated SPIRE 240 solar simulator. The calibration value of the reference cell is obtained by multiplying the known calibration of the primary cell by the ration of short circuit current (reference) to short circuit current (primary) [8]. The calibration was performed at a cell temperature of 25°C and effective incident of 100 mW/cm^2 . The calibration constant is $1.15 \pm 0.023 \text{ mA/mW/cm}^2$. The apparatus used to perform electrical isolation test is called Hi-Pot test unit as seen in fig. 1.

The thermal infrared test is used to determine whether or not the module is sufficiently well insulated. The purpose of this test is to determine the ability of the module to withstand the effects of localized heating due for example to a fault in the solar cell (cells incompatible, bad interconnect...) or the deterioration of the encapsulant by using the principle of thermal imaging based on an infrared camera as

a non-destructive analysis technique. Generally a photovoltaic module at 50 ° C emits heat mainly in the range of wavelengths from 3-20 μm with peak emittance at about 9 μm [5]. The infrared camera used in this work is the Avio TVS 700 type. Infrared thermography image reflects the temperature distribution over the entire surface of the PV module under forward polarization in the dark room temperature. The purpose of this polarization by external voltage source is to induce current conduction of solar cells. Fig. 2 shows the experimental set up for infrared thermal test.



Fig.1. Electrical isolation test apparatus



Fig.2. Thermal infrared experimental set-up

The outdoor measurements were performed on the site of university of Bechar located in the south of Algeria as specific desert climate environment, characterized by high irradiation and temperature levels. The annual average energy at latitude site of Bechar is about 5kWh. Experiments are carried out using a modern test facility containing a data acquisition system based on Peak Power Measuring Device Tracer (PVPM 2540C) as illustrated in fig. 3. It is a portable array tester and it uses a discharged capacitor that functions as load resistor. A calibrated reference solar cell used in our experimental investigation for measuring irradiance and cell temperature. It consists on mono-crystalline silicon solar cell with integrated Pt 1000 temperature sensor (Fig. 4).



Fig. 3. Representation of experimental set up based on data acquisition PVPM 2540C



Fig.4. Reference solar cell

3 Results and discussions

3.1 Current- voltage characteristics measurements

The PV module current-voltage characteristic under a pulsed light simulator and at STC is represented in fig. 5. The electrical properties of a PV module comprises of seven parameters: Open circuit voltage, V_{oc} ; Short circuit current, I_{sc} ; Maximum voltage, V_{mp} ; Maximum current, I_{mp} ; Maximum power, P_{max} ; Solar cell conversion efficiency, η_c ; PV module conversion efficiency, η_m ; and fill factor, FF. It can be observed that the measured maximum power is about 95 % of that specified by the manufacturer.

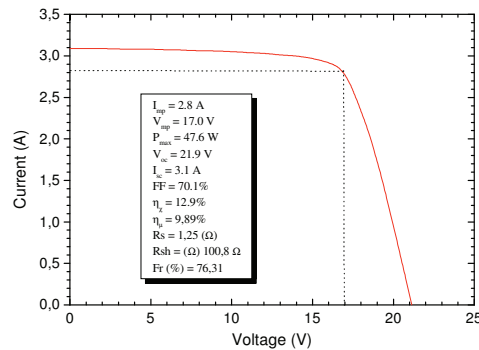


Figure 5: I-V curve of PWX 500 PV module at STC conditions

The procedure used for dark I-V measurements on PV module involves covering all solar cells to eliminate light generated current. This is done by using a power supply to force the generation of electrical current through the cell, and then measuring current and voltage simultaneously as the voltage of the power supply is increased from zero to a predetermined upper limit. The power supply can be applied in forward or reverse bias as shown in figure 2. As a result, dark I-V measurements can be used like light I-V measurements to analyze the electrical characteristics of a cell [6].

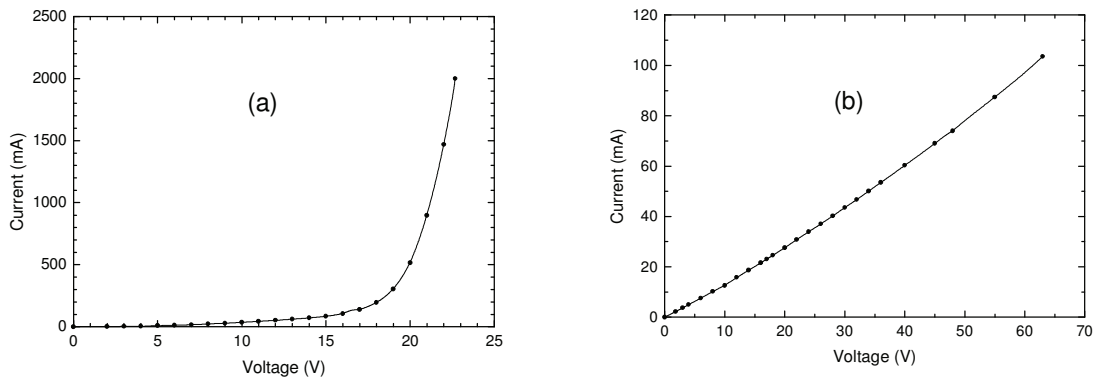


Fig. 6. PV module dark I-V measurements: (a) Forward bias, (b) Reverse bias

3.2 Insulation test

The maximum applied voltage is equal to 1000V plus twice the maximum system voltage (i.e. the open circuit voltage of the system: generally 600V) according to IEC 61215 [7]. Then, the insulation resistance is less than 50 M Ω and there is no evidence of dielectric breakdown or surface tracking.

3.3 Determination of temperature coefficients

Temperature coefficients play an important role in PV system design and sizing. They provide calculation tools to system designers for predicting how the cell, module and array will behave in operation. Procedures for measuring these parameters are standardized in the IEC 61215 [8]. The complete current-voltage characteristic may be measured at each temperature. The procedure consists to plot the values of I_{sc} , V_{oc} and P_{max} as function of temperature and construct at least square fit curve through each set of data. From the slope of each plot at a point midway between the minimum and maximum temperature of interest, we calculate the corresponding temperature coefficient for the PV module. Figures 7-8 show the variation of I_{sc} , V_{oc} and P_{max} as function of temperature respectively. The temperature coefficients of I_{sc} , V_{oc} and P_{max} are 2.92 mA/ $^{\circ}$ C, -84.1 mV/ $^{\circ}$ C and -0,19 W/ $^{\circ}$ C respectively.

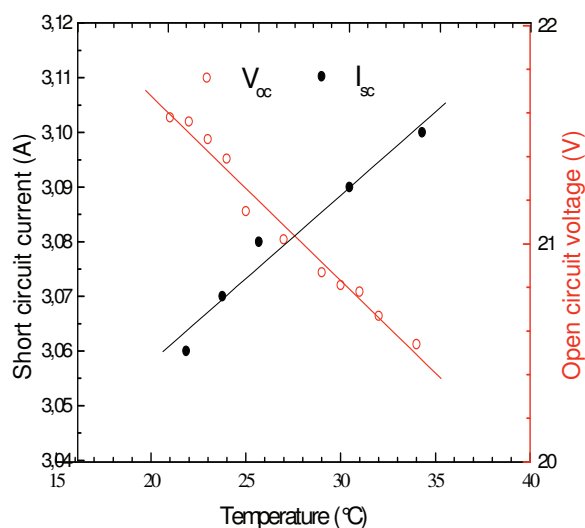


Fig. 7. Variation of short circuit current and open circuit voltage as function of temperature

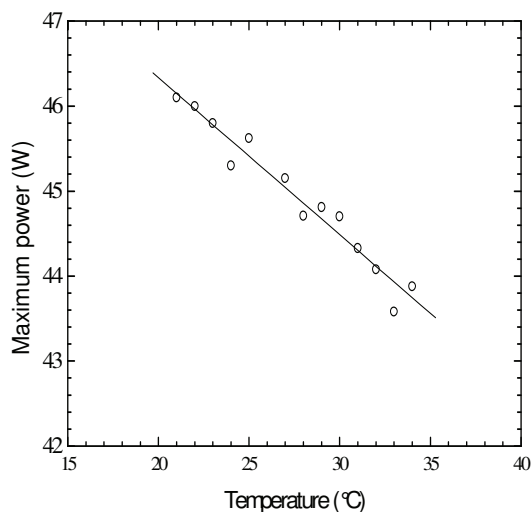


Fig. 8. Variation of maximum power as function of temperature

3.4 Determination of nominal operating cell temperature (NOCT)

Nevertheless, in real operating conditions the modules are normally not under standard condition. So another condition was defined, named normal operating condition, which presents the PV module performances under nominal operating cell temperature (NOCT). In this case the temperature of the PV module will depend on the ambient temperature, speed of the wind and the module thermal performance. The NOCT conditions are defined by the following values: Irradiance = 800 W/m^2 ; Ambient temperature = 20°C ; Wind speed = 1 m/s ; Spectral distribution = AM 1.5. The NOCT is defined as the equilibrium mean solar cell junction temperature within an open rack mounted module in the described standard reference environment. With a minimum of 10 valid points, the determination of NOCT is possible by plotting module temperature against the irradiance and performing a linear regression on the data according to IEC 61215 [9]. Figure 9 shows variation of $(T_c - T_a)$ as function of irradiance, we deduce that the value of NOCT is 48.8°C . The PV module I-V characteristic at NOCT is described in figure 10.

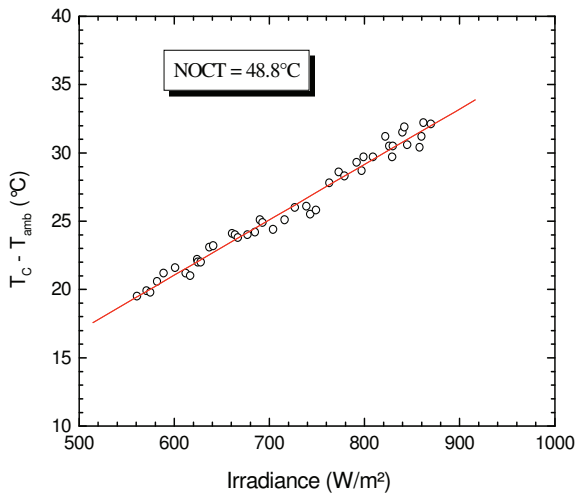


Fig. 9. NOCT determination procedure

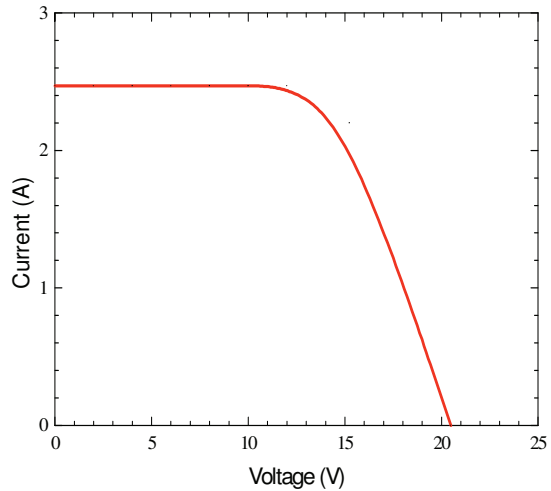


Fig. 10. Electrical performance at NOCT

3.5 Determination of Hot-Spot endurance

This test is devoted to determine the ability of the module to withstand Hot-Spot heating. This defect can be provoked by cracked or mismatched cells interconnect failures, partial shadowing or soiling. Hot-spot heating occurs in a module when its operating current exceeds the reduced short circuit current of a shadowed faulty cells or a group of cells within it [10,11]. When such a conditions occurs, the affected cell or group of cells is forced into reverse bias and must dissipates power, which can cause overheating. Figure 11 illustrates the hot spot effect in a PV module when solar cell is occulted at 64 % corresponding to maximum dissipation. Figure 12 shows the I-V characteristics of the PV module PWX 500 with and without protection diodes under STC conditions corresponding to the phenomenon Hot-Spot. We conclude that under the conditions of the phenomenon Hot-Spot the relative variation of the maximum power of PV module PWX 500 with and without protection diodes is 59% and 61% respectively. The effect of protection diodes is clearly shown to prevent the destruction of the solar cell. We note that the occulted solar cell under the conditions of the Hot-Spot is operating in reverse bias at a voltage of -14 V with a power dissipation of about 42 W .

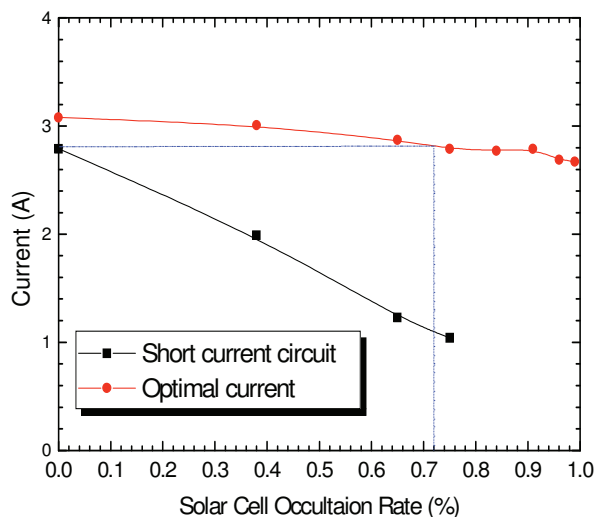


Fig 11: Hot-Spot conditions determination

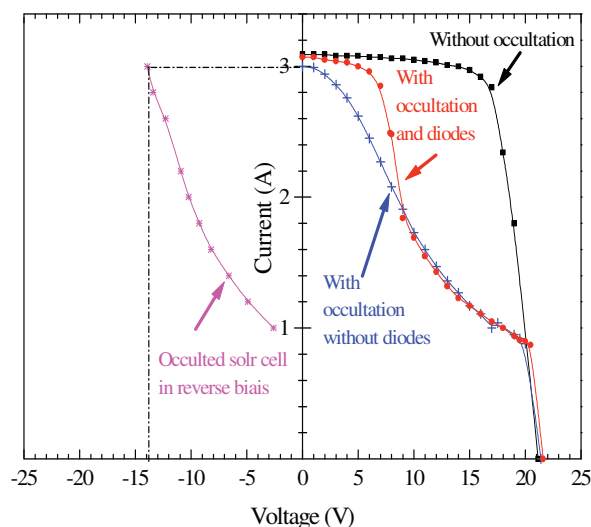


Figure 12: I-V characteristics at Hot-Spot conditions

3.6 PV module infrared thermography

Fig. 13 shows the infrared thermography image of the PV module under a bias current of 6A at testing start. The ambient temperature of the experiments is 30° C and the PV module has a low temperature of 34.2 ° C and a high temperature of 37.4 ° C. The medium temperature distribution across straight line of the PV module is 36°C.

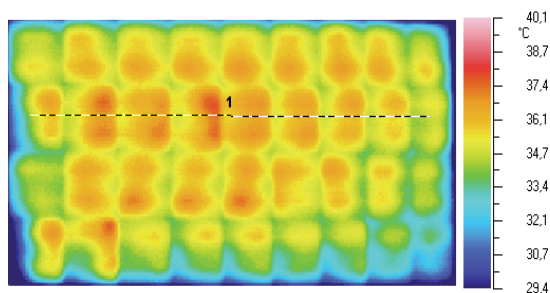


Fig. 13: Isotherm of the inspected PWX 500 PV module under forward power polarization of 6A and at testing start

Moreover, line profile analysis (LPA) produces graphs by linear and orthogonal regions of interest (ROI) showing the temperature fluctuation across the length of each ROI in pixels scale. In particular, fig.14 shows the thermal image with the linear ROI 1, 2, 3, 4 (a) and the corresponding generated line profiles (b) respectively of the PV module under a bias current polarization of 6A one 1 hour later.

The temperature homogeneity distribution of the PV module was examined across each ROI line as straight line LPA in the middle area of the horizontal string of 11 normally operating solar cell. It is noted

that the module temperature equilibrium was reached after one hour under direct current polarization. The PV module has a low temperature of 42.7 °C and a high temperature of 46.9 °C. In indoor experiments we found that it takes about 1 hour for a PV module to reach its equilibrium temperature. Generally, the equilibrium temperature depends on technology of PV module and their packing factor.

For the requirements of the measurements, the value of emissivity (ϵ) was adjusted with the thermal camera settings at 0.85 (glass and EVA regions), while for the mc-Si the right value is $\epsilon = 0.65$. This difference induces an error that influences the accuracy of the measured temperature values of the silicon surface (where $\epsilon = 0.65$). However, the described error does not affect the needed measurements which are related only with the mc-Si solar cells [12].

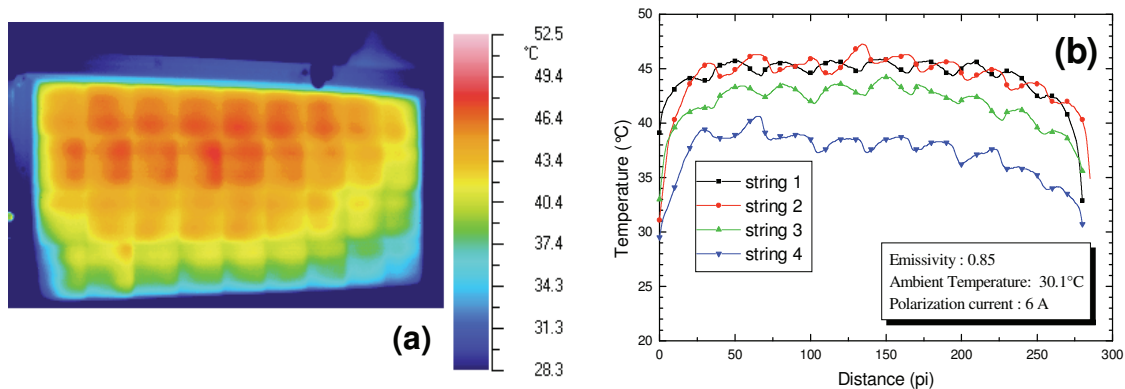


Fig. 14: Infrared image of PWX 500 PV module under forward power polarization of 6A after 1 hour: (a) Isotherm mapping, (b) Temperature profile

3.7 Electrical performances at outdoor exposure

The PV module under test receives an electrical performance I-V, under environmental conditions for different values of solar irradiance and ambient temperature, on a clear sunny day according to IEC 61215 [12] as shown in Fig. 15. There were many tests carried out when the working temperature and irradiance lay in the ranges of 42-64°C and 400-1002W/m² respectively. In outdoor exposure of Bechar climate and during the test, the working temperature of PV module was measured as high as 64°C as described by the plot of PV module temperature evolution in figure 16.

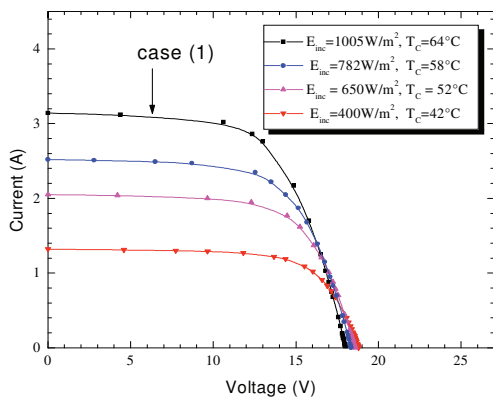


Fig 15: PV module I-V characteristics in outdoor testing

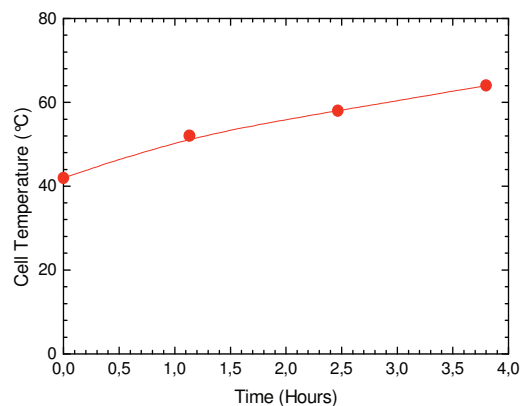


Fig 16: PV module temperature evolution in outdoor testing.

In case (1) a slight increase in the short circuit current of the module was noted that for a working temperature of 64°C with irradiance equal to 1005 W/m². Under these operating conditions our module lost a minimum of 31% efficiency, 18% of the maximum output power and 18% of the fill factor compared with that at STC in indoor conditions.

When the determination of a PV module characteristic curve is performed outdoor, most of the times the module is not likely to be under standard conditions. For this reason, the test is taken under any condition that satisfies the standards minimum requirements and the collected points of the I-V curve are mathematically translated to the standard conditions. Therefore, Data acquired was converted into PV module characteristics at STC conditions by using the conversion method suggested by G. Bleasser [14]. By this method the PV module maximum is found to be 46.6 W.

Generally, the PV module maximum power is determined by using the solar simulators (pulse-light or continuous-light solar simulator) that represent an artificial and controlled environment. This type of measure does not represent a natural environment and therefore our results should differ from those obtained in indoor testing. Nevertheless these findings challenge and call for caution when using the electrical ratings of a PV device at STC for the design of a PV generator/system for any locality on the globe without considering how the climate of that locality affect the performance of the PV system [15].

Conclusion

Tests developed in this paper permit a rapid quality control of PV module within manufacturer data. Also, infrared thermography appears to be a potential non-destructive method for the in situ evaluation of a PV module performance. The method gives fast, quite reliable and of easy interpretation results regarding to the condition of each solar cell in a PV module. Unfortunately, specific limitations referring to emissivity problems, the presence of glass in front of the solar cells and the undesirable dependency from the environmental (ambient and background) conditions have to be taken into account. It is established that an increase in the working temperature of PV module alters their electrical performance. We have investigated how an increase in the temperature influences the electrical properties of PV module in a controlled environment using a sun simulator. In these experiments, all other variables for example, irradiance, wind speed, etc are kept constant. These hypothetical and artificial operating conditions cannot be simulated in a natural sunlight where a number of micro-climatic parameters along with the temperature simultaneously drive the PV module. A temperature in a natural environment is no longer a single valued function as in the case of controlled environment. Our results quantitatively should differ due to two different testing modes.

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